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Precision in Scanning Applications through Innovative Flexure Mechanism Development

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A B S T R A C T

The Planar XY Flexural Mechanism finds extensive use in precision motion systems, facilitating relative motion between a fixed support and a motion stage through material flexibility. Unlike rigid link mechanisms, this design offers significant advantages such as zero backlash, frictionless motion, and high-order repeatability, all in a more compact form factor. Notably, flexure mechanisms are constructed from a single monolith, a characteristic emphasized in this research. The focus is on modeling the flexural process to achieve precise scanning over a broader range at increased speeds. Finite Element Analysis (FEA) is employed for static analysis to assess the motion stage's static deflection. Subsequently, the mechanism is activated using a weight pan and weights, with displacement monitored via a Dial Gauge Indicator. The experimental setup includes components such as the flexural mechanism, Dial Gauge, Weight Pan and Weights, Pulley, String, Small metal strip, and Optical Bread Board. Comparison of experimental and analytical findings reveals minimal variation, confirming the effectiveness of the flexural mechanism in providing precise motion for high-precision applications.

Keywords: ANSYS, FEA, Flexure, Precise

1. Introduction

Increasing demands in materials research, electronics, and advanced manufacturing have driven the need for ultra-precision methods. Compact planar XY flexure stages have emerged as essential solutions, offering extensive motion capabilities and finding diverse applications in fields such as wafer alignments, semiconductor masks, atomic force microscopy, scanning interferometry, micromanipulation, micro-assembly, and high-density memory storage [1-4].

Micro-positioning stages, vital for precise maneuvering of end-effectors with specific degrees of freedom (DOF) and submicron positioning resolution, require characteristics like a broad workspace, high resolution, compact size, and high bandwidth. Previous research has aimed at enhancing the performance of micro-positioning stages [5-9]. A unique compact high-precision XY scanner has been developed, featuring a millimeter-level operating range and nanometer-level resolution, striking an optimal balance among design factors [10-14]. This scanner incorporates an actuator and double compound linear spring flexure guiding mechanisms to meet accuracy and travel range standards while minimizing parasitic motion during scanning [15-19].

Nano and micro-positioning mechanisms are pivotal in advancing precision mechanisms with exceptional cost-performance characteristics, especially in small-scale technologies [20-24]. This paper elaborates on a planar 3-DOF parallel-type micro-positioning mechanism focusing on precise flexure hinge modeling. Accurate modeling of the flexure hinge mechanism is crucial to enhance Microsystems' positional precision, enabling their utilization in x-ray lithography, micromachining, scanning electron microscopy (SEM), and mask alignment [27-31]. Flexures, operating on material elasticity [32], demonstrate precision in motion and are applied in high-speed scenarios due to molecular-level anamorphosis.

2. Design of Flexure Mechanism

The flexure mechanism enables precise motion by allowing relative movement between the motion stage and a fixed support. Figure 1 illustrates the generation of this relative motion using an interface element. Traditional interface components like sliders, ball bearings, and liquid or air films, which are often associated with friction and backlash issues, do not provide significant advantages in terms of high accuracy and repeatability [3,33-35]. To mitigate friction and backlash concerns, these components can be replaced with flexible counterparts such as hinges and flexible beams. This substitution offers additional benefits, facilitating high-precision scanning with an elevated level of repeatability [36-39]. Based on this fundamental concept, various flexure mechanisms, including XY configurations, have been developed.

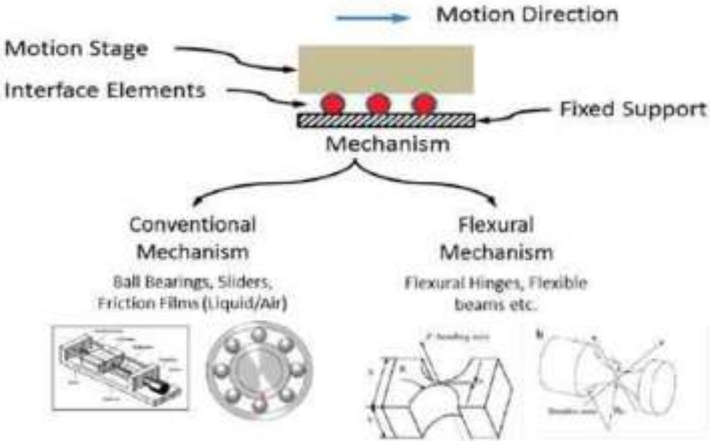

Fig. 1 - Interface Element of the Mechanism [1]

3. Experimental Setup

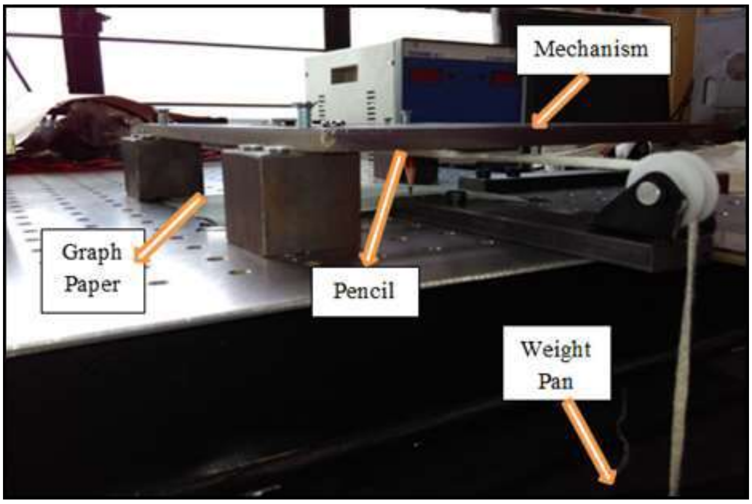

Fig. 2 - Experimental Setup for Flexure Mechanism

The entire mechanism is securely mounted on a vibration-free foundation using four metal mounting blocks fastened with M6 bolts. The comprehensive experimental setup includes the mechanism itself, Dial Gauge indicator, Pulley, String, weight pan, small metal strip, g-clamp, and an Optical Bread Board. The weight pan serves as the actuation component, connecting to the flexural mechanism in the X-Y direction through a g-clamp linked to a pulley via a string.

An essential instrument in the setup is an analog Dial Gauge Indicator, measuring displacement in the X-Y direction. A Small Metal Strip is attached to the motion stage, extending to provide measurements to the dial gauge. The Optical Bread Board acts as a stable, vibration-free foundation for attaching the mechanism. Experimental observation of the flexure mechanism is conducted in both the X and Y axes, with varying load values ranging from 1 N to 25 N. The specific displacements corresponding to these diverse load conditions are detailed below.

Table 1 - Testing Results in the X and Y Directions

Applied Force in N	X direction FEA output in mm	Y direction FEA output in mm
2	0.49	0.42
6	1.81	2.1
12	3.87	4.112
15	5.89	6.2
20	7.81	8.25

4. ANSYS Results

Finite Element Analysis (FEA) is employed to evaluate the displacement and maximum stresses of the flexure mechanism. Force is applied in both the X and Y axes during the analysis. ANSYS tools are utilized for a comprehensive investigation of the flexure mechanism.

The graphs depicting various outcomes are presented in Figure 3 and Figure 4.

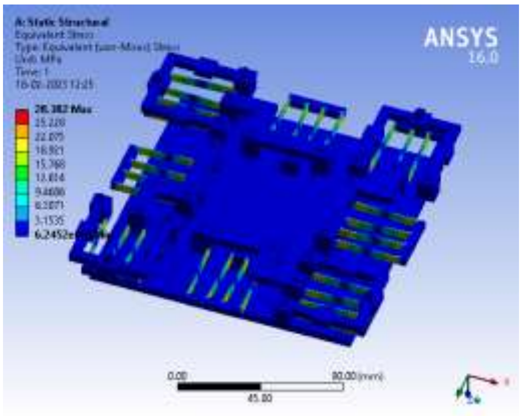

Fig. 3 - Analysis of XY Flexure Mechanism and Application of Force in the X-Direction

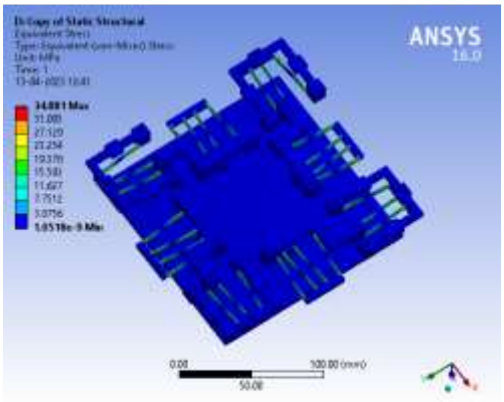

Fig. 4 - Analysis of XY Flexure Mechanism and Application of Force in the Y-Direction

Table 2 - FEA Results for X and Y Direction Outputs

Applied Force in N	X direction FEA output in mm	Y direction FEA output in mm
2	0.55	0.521
6	2.028	2.24
12	4.24	4.541
15	6.345	6.541
20	8.25	8.654

5. Result and Discussion ON FEA and Theoretical

Experimental displacements are cross-validated using numerical methods for both the X and Y directions. The outputs obtained through experimental and numerical calculations, along with the corresponding error values, are presented below.

Table 3 - Analysis of Experimental and Numerical Displacements in the X-Direction

Applied Force in N	X Direction output Experimental result in mm	X Direction output FEA result in mm	% of Error
02	0.49	0.55	10.90909
05	1.81	2.028	10.74951
10	3.87	4.24	8.726415
15	5.89	6.345	7.171001
20	7.81	8.25	5.333333

When comparing experimental and numerical outputs, the table above shows a maximum error of 10.490% and a minimum error of 5.33%. The observed average error is 7.501%.

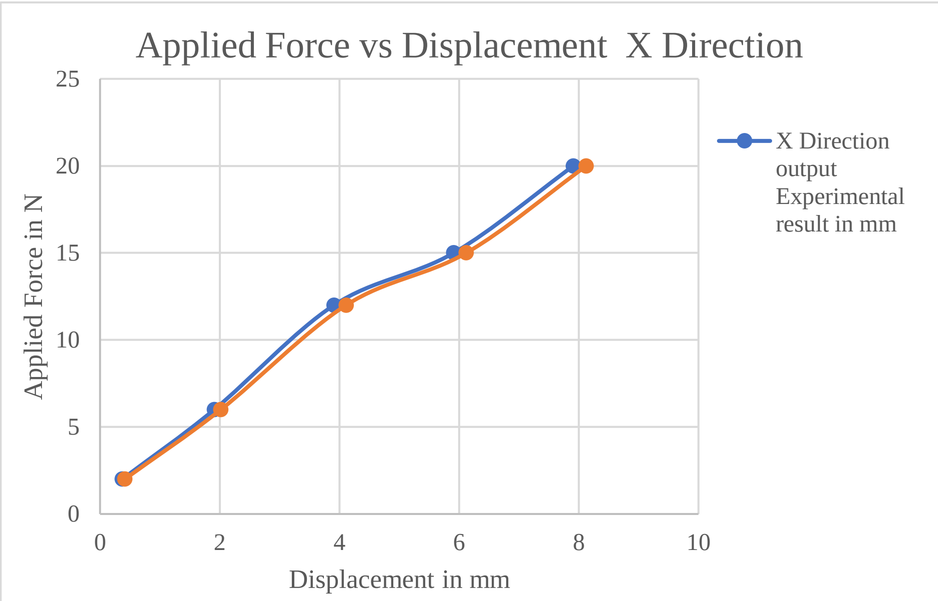

Fig. 5 - Comparison of Experimental and FEA Analysis for X-Direction

Table 4. Analysis of Experimental and Theoretical Deformation in the Y-Direction

Applied Force in N	Y Direction output Experimental result in mm	Y Direction output FEA result in mm	% of Error
02	0.42	0.521	19.3858
05	2.1	2.24	6.25
10	4.112	4.541	9.447258
15	6.2	6.541	5.21327
20	8.25	8.654	4.668361

When comparing experimental and numerical results, it is clear from the table that there is a maximum error of 19.38% and a minimum error of 4.66%. The observed average error is 8.059%.

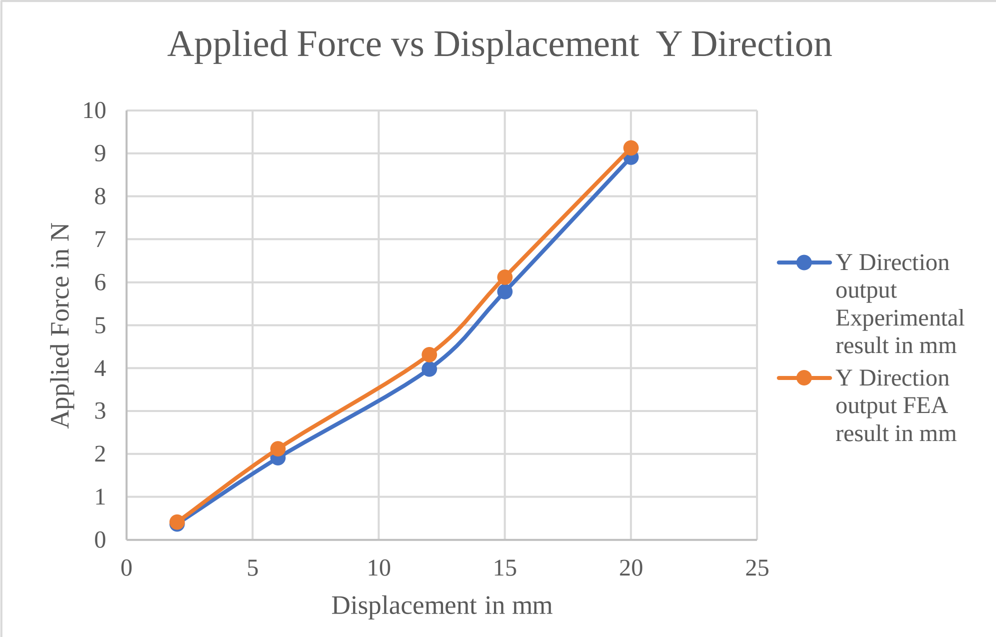

Fig. 6 - Comparison of Experimental and FEA Analysis for Y-Direction

6. Conclusion

The Motion Stage exhibits precise travel in both the X and Y axes. At maximum operating load, experimental and numerical studies indicate an X-direction displacement of 7.17 mm and 8.13 mm, respectively. Additionally, under maximum working load, experimental and numerical studies reveal Y-direction displacements of 8.51 mm and 9.011 mm, respectively. The experimental findings closely align with the numerical results, showing a 10% margin of error. This close agreement between experimental and computational data suggests that the constructed model excels in performance compared to the flexure mechanism. The XY Flexure mechanism, renowned for its ability to generate repeatable and smooth motions, finds applications in precision-oriented sectors such as laser printing and scanning, microscopy, and micro-nano manufacturing systems.

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